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EMI and EMC Test Methods

36.1 Introduction

Electric and magnetic fields must be measured for a variety of reasons. A radio or TV broadcast station is licensed to provide reliable coverage over a specified geographic area, and any properly operating receiver must pick up the signal and properly respond to it. This can be assured only if the broadcast signal is of a guaranteed minimum strength. Also, the signal must not be so strong that it interferes with a distant station sharing the same frequency. The broadcast field must be measured over its geographic area of coverage to be sure that it satisfies both criteria.

Many electric devices unintentionally radiate electromagnetic fields. Examples include:

- Oscillators in superheterodyne radio or TV receivers
- Digital logic circuits
- Switching contacts, particularly if unsuppressed
- Automotive ignition systems

Stray fields (emissions) from these devices can interfere with other devices or even with the radiating device itself. This process is known as electromagnetic interference, commonly abbreviated EMI. The interference between two devices is known as intersystem EMI, whereas if a device interferes with itself, it is intrasystem EMI. Intrasystem EMI is usually easy to spot because the device itself does not operate correctly. Intersystem EMI is usually more difficult to isolate. Its result might be a simple annoyance, such as noise on a radio and TV receiver caused by an electric vacuum cleaner or a power drill. It could, however, be much more serious; a portable radio receiver might affect aircraft navigation or critical communications.

It is also possible for a device to be susceptible to fields intentionally generated by a licensed transmitter such as a broadcast or mobile-radio transmitter. Examples include:

- Public-address systems
- Music (high-fidelity) systems
- Telephone lines and instruments
- Digital logic circuits
Again, the result may be only an annoyance, or it could be much more serious; aircraft control surfaces have been observed to move uncontrollably due to strong electromagnetic fields. Since the fields themselves cannot be eliminated in these cases, the devices must be made immune to electromagnetic fields.

In the previously mentioned cases, the interference is usually through electric and/or magnetic fields in space, so the process is known as radiated coupling. Another coupling path exists if two devices share the same power source. One device may generate undesired high-frequency voltages on its power leads, which then appear on the power leads of the other. The second device may then malfunction because of this high-frequency voltage. This is known as conducted coupling. So we must consider both radiated and conducted noise.

It is not practical to eliminate all interfering fields completely, so a compromise must be reached. A stray field will not cause EMI if it is very weak compared with the desired field, which might be the field of a broadcast signal. The permissible strength of the stray field depends on the strength of the desired field; the stronger the desired field, the more stray field can be tolerated. It also depends on the device that is being interfered with (the victim); some receivers can reject undesired signals better than others. Since there are many combinations of interference sources and victims, a worst-case scenario is sought that will protect most real-life situations. This occurs where the weakest legal radio or TV signal (in its licensed area of coverage) is received by the poorest available receiver.

The maximum stray field strength that causes no EMI for this worst-case scenario is incorporated into government regulations. The field actually radiated by every device must then be measured to be sure that it does not exceed this level at the nearest practical distance from it, usually 10 or 30 m. To specify and measure these fields accurately, the nature of electric and magnetic fields must be understood.

Unlike most electrical engineering topics, EMI control is not very precise because of the complexity of practical hardware. It is virtually impossible to predict interference more precisely than within a factor of three, and usually the margin of error is even worse. Measurements can vary significantly between two supposedly identical samples, due to slight variations in physical dimensions. If one measures the EMI resulting from two different designs, the design that exhibits less EMI is probably better, but not always. An engineer can often judge if an EMI problem exists, but one must never rely on the accuracy normally expected in other branches of electrical engineering.

### 36.2 Nature of Electric and Magnetic Fields

An electric field is generated by a distribution of electric charge. If the distribution changes with time, then so will the electric field. A magnetic field may be generated by a permanent magnet or by an electric current. If the permanent magnet or the current path moves or if the current magnitude varies with time, the magnetic field will vary with time. A time-varying electric field creates a magnetic field, and conversely.

Electric fields, designated $E$, are normally expressed in volts per meter (V/m). Magnetic fields are designated $H$ and expressed in amperes per meter (A/m). More often, magnetic fields are perceived as magnetic flux densities, which are designated $B$ and expressed in webers per square meter (Wb/m$^2$), also known as teslas (T). A non-SI unit, sometimes found in older literature, is the gauss, equal to $10^{-4}$ T. Of course, any unit may be preceded by a scaling prefix such as micro or pico. In free space, $B$ is equal to $\mu_0 H$, where $\mu_0$ is equal to $0.4\pi$ (approximately 1.257) $\mu$T mA (equivalent to $\mu$H/m).

Near a time-varying electric field source such as a charge distribution, the magnetic field is relatively weak, but it becomes stronger when observed from farther away. At a great enough distance, the ratio of $E$ to $H$ approaches $\sqrt{\mu_0/\varepsilon_0}$, where $\varepsilon_0$ is the permittivity of free space and is equal to $120\pi$ (approximately 377) $\Omega$. For a sinusoidal function of time with a frequency $f$, this occurs at any distance that is large compared with $\lambda/2\pi$ (approximately $\lambda/6$). Here, $\lambda$ is the wavelength corresponding to $f$, equal to $3 \times 10^6 f$ m if $f$ is specified in hertz. Distances much greater than $\lambda/2\pi$ are considered to be in the far-field region; nearer distances are in the near-field region. For a nonsinusoidal function of time, each Fourier frequency component must be considered separately, and the far-field region begins closer to the source for its higher-frequency components.
Near a time-varying magnetic field source such as a current loop, the electric field is weak, becoming stronger when observed from a greater distance. At distances that are large compared with λ/2π (the far-field region), the ratio of E to H again approaches 120π Ω.

Since \( H = \sqrt{\mu / \varepsilon} E \) and \( B = \mu H = \sqrt{\mu / \varepsilon} E \) in the far-field region for either type of source, only E or B must be measured, and the other can easily be calculated from it. In free space, \( \sqrt{\mu / \varepsilon} \approx 10^{-3}/377 \text{ T} \cdot \text{m/V} \) (equivalent to s/m), so if \( E \) is expressed in volts per meter, \( B \approx 3.33E \text{ nT} \). By choice of a suitable antenna, either field can be measured. Far-field strengths are normally specified in terms of the E field, no matter whether the E or B field is measured.

Alternately, the far-field strength may be specified in terms of power density, expressed in watts per square meter. \( T \) is the amount of radiated power passing through each square meter of a surface perpendicular to the direction away from the source. The peak power density \( P \) is equal to \( EH \), and, for a sinusoidal source, the average power density is half this value. For a nonsinusoidal source, each frequency component must be considered separately, and the total average power is the sum of the average powers for all frequencies. Since \( H = \sqrt{\mu / \varepsilon} E \), it follows that \( P = E^2/377 \Omega \).

In regions other than the far-field, the ratio of E to H varies greatly, approaching infinity for an electric field source or zero for a magnetic field source. A source may generate both electric and magnetic fields; for example, a charge moving between two electrodes causes a current to flow between them. Then the ratio of E to H may be any value at all. Therefore, at distances less than \( \lambda/2\pi \) from a field source, both the E and B fields must be measured separately.

In the far-field region, both the electric and magnetic fields are perpendicular to the direction that an electromagnetic wave is propagating, and they are also perpendicular to each other. \( T \) is still usually observed to be oriented at many different angles with respect to the surface of the Earth. The direction of the electric field is called the polarization of the wave, which may be vertical, horizontal, or somewhere between. Or the wave may be elliptically polarized, which results from two waves that are not exactly in phase, one polarized vertically and the other horizontally. If the waves are equal in magnitude and exactly 90° out of phase, the wave is circularly polarized. To account for all these cases, all fields must be checked separately for vertically and horizontally polarized waves.

### 36.3 Measurement Antennas

Most electronic components and instruments are designed to respond to voltages or currents, not fields. To measure field strength, it is necessary to convert its effect to a voltage or a current. \( T \) is achieved by an antenna. Although many antennas are simple conductor shapes, they must be analyzed carefully if accurate quantitative measurements are desired.

A straight conductor immersed in a time-varying electric field will develop a current in it. If the conductor material is linear (the usual case), the current will be proportional to the applied electric field, so their ratio will be constant. \( T \) is ratio, however, depends greatly on the geometric dimensions of the conductor and the frequency of the electric field. It must be known to calibrate the antenna.

Similarly, a closed conductive loop immersed in a time-varying magnetic field will develop a current in it. Again, if the conductor is linear, the ratio of the current to the magnetic field strength is constant but depends on the dimensions of the loop and the frequency of the magnetic field.

The easiest way to calibrate an antenna is to immerse it in a known electric or magnetic field and measure the current or voltage at the antenna terminals. The principal problem is generating the known field. To find its strength, one must use a “standard” antenna for which the current-to-field ratio can be calculated.

To calculate the required ratio, Maxwell’s equations must be solved subject to the boundary conditions of the antenna conductor. For most antennas, an exact closed-form solution is impossible. However, for a sinusoidally varying field encountering a straight cylindrical conductor called a dipole antenna, such a solution is possible, though difficult [1]. Once the solution is obtained, the required ratio becomes a simple expression if the antenna is resonant or tuned. \( T \) is for a precise length that
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is slightly less than one-half the wavelength, \( \lambda \), of the time-varying field. Obviously, the antenna will be resonant at only one frequency, so the ratio will be valid only for a field varying sinusoidally at that frequency. For nonsinusoidal fields, each Fourier frequency component must be measured separately, and the antenna length must be changed as different frequencies are measured. To simplify changing its length, two telescoping rods, mounted end to end, are normally used to make the dipole antenna. The measuring instrument is connected between these two rods via a transmission line.

For a given frequency, at any point on the antenna, there is a certain current \( I \) owing in it, and there is also a certain voltage \( V \) on it with respect to ground. The ratio of these phasors, \( V/I \), is known as the driving-point impedance. The precise resonant antenna length is that for which \( V \) and \( I \) are exactly in phase, that is, for which the driving-point impedance is purely real. As mentioned earlier, this length is slightly less than half the wavelength, \( \lambda \), and it also depends on the thickness of the telescoping rods [1, pp. 547–548]. For a rod thickness of \( \lambda/400 \), the resonant length is \( 0.476\lambda \). The driving-point impedance of a dipole antenna of these dimensions is \( 64 \Omega \). If a voltage-measuring instrument such as a radio receiver or spectrum analyzer is connected to the antenna terminals via a transmission line and is properly matched to the 64 \( \Omega \) impedance, the measured voltage \( V_m \) will be equal to 0.148\( I \), where \( I \) is the applied field strength and \( \lambda \) is the wavelength at the frequency being measured. The ratio \( V_m/I \), equal to 0.148\( \lambda \), is known as the effective length (\( l_e \)) of the antenna, since it relates the field strength in volts per meter to the measured terminal voltage in volts. Obviously, it is not equal to the physical antenna length but is instead approximately one-third of that value. With this ratio known, the electric field strength \( E \) that causes a certain terminal voltage \( V_m \) can easily be calculated.

To simplify calculations, \( E \) is often expressed in decibels with respect to a reference field of 1 \( \mu V/m \) and is designated \( E_d \). Similarly, \( V_m \) is expressed in decibels with respect to a reference voltage of 1 \( \mu V \) and is designated \( V_d \). The antenna factor (AF) is defined as the effective length expressed in negative decibels, or AF = \(-20 \log(l_e)\). The multiplication becomes an addition, that is, \( E_d = V_d + \text{AF} \).

The aforementioned AF assumes that the antenna is perfectly matched to the receiver, which implies maximum power transfer. An mismatch would change the AF. Therefore, since the antenna driving-point impedance usually is not equal to the receiver input impedance, a matching circuit must be inserted between the antenna and receiver. Another essential consideration is antenna balance. Most receivers and spectrum analyzers have one input terminal grounded. If this grounded terminal is connected to one of the dipole antenna terminals, the impedances connected to the two antenna terminals will be unequal with respect to ground. This will also upset the AF, since one side of the antenna will not be properly matched to the receiver. To prevent this, a balanced-to-unbalanced (balun) network must be inserted between the antenna and the receiver. Such a circuit provides a high impedance with respect to ground for both input terminals while providing the correct input impedance (such as 64 \( \Omega \)) between its input terminals. Normally, a single network provides both the matching and balancing functions.

Unfortunately, unless the dipole antenna is precisely the correct length, its AF is much more complicated. Even if the frequency being measured differs only a few percent from the antenna resonant frequency, the AF becomes unpredictable and the driving-point impedance becomes complex. Thus, the electric field cannot be easily calculated from the measured terminal voltage. To achieve the simple AF described earlier, the frequencies must be measured one at a time and the dipole antenna length properly adjusted for each frequency. It is impossible to sweep the spectrum rapidly, as when using a spectrum analyzer, unless the antenna length can somehow be varied also. This leads to mechanical difficulties and is usually impractical.

Other types of antennas, however, are less sensitive to frequency. Examples are the biconical antenna and the log-periodic antenna. A biconical antenna can perform acceptably over a range of 20–300 MHz, and a log-periodic antenna is useful from 300 to 1000 MHz. Their AFs are relatively constant, usually varying by no more than 20 dB, over their useful frequency ranges. Their AFs are usually too difficult to calculate, but they may easily be measured simply by observing the terminal voltage resulting from a sinusoidally varying field of known strength. The known field is first measured using a tuned dipole...
antenna, for which the AF can be calculated. The AF is measured in this manner at several frequencies throughout its useful range, and the results are plotted for use with the antenna.

Unlike the tuned dipole, the biconical and log-periodic antennas do not exhibit constant driving-point impedances over their useful frequency range. Since the receiver input impedance cannot be made to follow the variation of driving-point impedance with frequency, an exact match is impossible. The effect acts the AF just as it would for a mismatched tuned dipole. To compensate for this, the AF must be measured with the antenna terminated into a known impedance, which must then be used for all measurements made with that antenna. Then the mismatch is accounted for in the AF itself. The mismatch does cause the antenna to reradiate the received signal, but this effect may be minimized by performing the measurements in an open-field site, which will be discussed later.

Tuned dipole, biconical, and log-periodic antennas are linearly polarized antennas because they respond to only one polarization component of a propagating wave. If the antenna is oriented horizontally, only the horizontally polarized component of the wave will affect it. Similarly, only the vertically polarized component will affect a vertically oriented antenna. Thus, with two measurements, any linearly polarized antenna will detect any type of field polarization. Other types of antennas, such as the spiral antenna, are designed to detect a circularly polarized wave. They will detect vertically and horizontally polarized waves, but they could miss a wave that is circularly polarized in the reverse direction (e.g., counterclockwise instead of clockwise). Consequently, circularly polarized antennas are forbidden for many types of field measurements.

All antennas discussed earlier respond to the electric field, $E$. As mentioned earlier, in the far-field region, the magnetic field, $B$, is simply 3.33 nT times the value of $E$ expressed in volts per meter. In any other region, however, $B$ is not so simply related to $E$ and must be measured separately, using an antenna that responds to magnetic fields. A circular loop or coil of wire is such an antenna. The loop is cut at one point, and the radio receiver or spectrum analyzer is connected between its two ends. For quantitative measurements, its AF must be known. The factor can be measured by immersing the antenna in a known magnetic field and measuring its terminal voltage. To find the known magnetic field strength, the electric field is first measured, in the far-field region, using a tuned dipole antenna for which the factor is known. The magnetic field is then 3.33 nT times this value expressed in volts per meter. With the magnetic field thus determined, the AF of the loop may be calculated, as required.

### 36.4 Measurement Environment

A major difficulty with electromagnetic field measurements is repeatability of results. Electromagnetic fields are affected by any materials in their vicinity, even by poor conductors and dielectrics. The measurement environment must therefore be carefully defined, and similar environments must be used for all comparable measurements.

The ideal environment would be one where (1) the only electromagnetic field source is the equipment under test (EUT) and (2) there is no “foreign” material at all that could affect the fields being measured. Unfortunately, the only natural location where this could be achieved is in outer space, since the Earth itself affects electromagnetic fields. Since this is impractical, attempts are made to simulate this environment on Earth.

A large outdoor open area simulates a hemisphere of free space. Such a test site is appropriately called an open-field site. If the conductivity, permittivity, and permeability of the Earth were constant, every open-field site would have the same effect on the electromagnetic fields radiating from the EUT. The Earth’s parameters do vary, however. To compensate for this variation, a large conductive floor, or ground plane, is laid under the EUT. This causes all electromagnetic waves to be totally reflected from the ground plane, so that the Earth’s properties have no effect. The ground plane must be large enough so that it appears infinite with respect to the EUT and the associated test equipment. Acceptable dimensions are $1.73d \times 2d$, where $d$ is the distance between the measurement antenna and the EUT, normally 3 or 10 m. Radiated emissions must be measured in all directions from the EUT.
and at various angles of inclination. This is most easily achieved by placing the EUT on a turntable, which is then rotated during the test. To allow measurement at various inclination angles, the receiving antenna height must be varied, and this is accomplished by mounting it on a halyard. A typical open-field site appears in Figure 36.1.

An open-field site provides repeatable data only if there are no nearby trees or structures that could cause undesirable reflections. Before it can be reliably used, it must be tested. This is done by generating a known electromagnetic field and measuring it. The field is normally generated by a radio-frequency oscillator driving a tuned dipole antenna, for which the radiation can be calculated ([2]: pp. 237–238). The radiation is then measured as though it were generated by a typical device being tested. The ratio of the voltage at the transmitting antenna terminals to that at the receiving antenna terminals is known as the site attenuation. If the site attenuation is within 3 dB of its calculated value, the test site is deemed acceptable.

Although an open-field site eliminates reflections, external field sources, such as licensed transmitters, still cause problems. Since electromagnetic radiation can travel thousands of miles, no open-field site will be completely free of electromagnetic fields. To eliminate the effects of these stray sources, testing must be performed inside a shielded enclosure. Here, however, severe reflections occur, and measurements become inaccurate and unrepeatable.

An ideal test environment would be a shielded enclosure lined with material that does not reflect electromagnetic waves. Such an enclosure is called an anechoic chamber, with the understanding that the name refers to electromagnetic echoes. Until recently, such chambers were not practical except at very high frequencies, but improvements are constantly being made. Such an enclosure is acceptable for testing if it meets the site-attenuation requirements of a true open field. The site attenuation must be measured at several points inside the chamber, to assure that the proximity of the chamber walls has no effect. Unfortunately, such chambers are at present very expensive.
Another type of test chamber is the transverse electromagnetic (TEM) cell. This consists of an enlarged section of waveguide, in which the electromagnetic fields can be accurately predicted [3,4]. TEMs are suitable only for testing small devices at relatively low frequencies. The TEM cell can be no larger than a wavelength at the frequency being tested. For example, to test at 200 MHz, the cell could be no larger than 1.5 m, or 5 ft, and the device itself must not exceed 1% of this value, or 10 in. For small devices, however, the TEM cell is very accurate and is unaffected by stray fields.

If a suitable anechoic chamber is not available, a device may be tested in an ordinary shielded enclosure to learn what frequencies it emits. The field strengths will be inaccurate due to the internal reflections. Even the device is tested in a true open-field site, and the suspected frequencies are measured quantitatively. Any field that exceeds the acceptable limits is then observed while the device is shut off. If it does not disappear, it is obviously not being generated by the EUT. This procedure is acceptable, although not as simple as testing inside an anechoic chamber.

Preliminary measurements may even be performed in an ordinary room. They will not be comparable with similar measurements made anywhere else, because of the effects of nearby conductors and dielectrics. Here, also, the device must be shut off to decide if any emissions are from stray external sources instead of from the EUT. This procedure provides a rough estimate of the emissions from the EUT, and it usually saves time during any later testing at a true open-field site. The various measurement methods appear in Table 36.1.

Permissible emission levels appear in the Code of Federal Regulations [5]. These rules assume open-field measurements, which are the most accurate possible. Even there, variations of ±6 dB are typical. Therefore, a manufacturer should allow a safety factor when performing measurements intended to assure compliance with government regulations. Otherwise, a device may pass when tested by the manufacturer but fail if later tested by the government using a supposedly identical test procedure. Since the government’s measurements then prevail, the manufacturer’s integrity could be questioned.

Further details on measurement techniques are available in Refs. [2,6].

**TABLE 36.1** Comparison of EMI Measurement Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Equipment Required</th>
<th>Space Required</th>
<th>Accuracy</th>
<th>Outside Influence</th>
<th>Cost</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary room</td>
<td>Antenna and receiver</td>
<td>3 or 10 m radius around EUT</td>
<td>Medium, affected by structure, ±20 dB</td>
<td>May be severe, depending on location</td>
<td>Minimum</td>
<td>Usually acceptable for preliminary tests</td>
</tr>
<tr>
<td>Shielded room</td>
<td>Shielded room, antenna, and receiver</td>
<td>4-6 m radius around EUT</td>
<td>Poor, ±30-40 dB due to reflections</td>
<td>Usually none</td>
<td>Moderate</td>
<td>Use for preliminary tests in noisy areas</td>
</tr>
<tr>
<td>TEM cell</td>
<td>TEM cell and receiver</td>
<td>1-3 m³</td>
<td>Very good, ±10 dB</td>
<td>Usually none</td>
<td>Moderate</td>
<td>Unusable for large EUT due to high-order modes</td>
</tr>
<tr>
<td>Open field</td>
<td>Antenna and receiver</td>
<td>17 x 20 m open field with no nearby structures</td>
<td>Excellent, usually ±6 dB</td>
<td>May be severe, depending on location</td>
<td>High</td>
<td>Standard test method</td>
</tr>
<tr>
<td>Shielded anechoic chamber</td>
<td>Anechoic chamber, antenna, and receiver</td>
<td>6-15 m radius around EUT</td>
<td>Very good, ±10 dB</td>
<td>Usually none</td>
<td>Very high</td>
<td>Use for accurate tests in noisy areas</td>
</tr>
</tbody>
</table>
Defining Terms

**Antenna factor**: Its effective length expressed in negative decibels.

**Balun**: An interface device used to isolate a dipole or other balanced antenna from the effects of a receiver having one grounded terminal.

**Conducted coupling**: Coupling due to voltages imposed on a shared power source.

**Dipole antenna**: An antenna consisting of two collinear rods with the feed line connected between them.

**Driving-point impedance**: The ratio of voltage to current at the driving point (normally the center) of an antenna.

**Effective length**: The ratio of the voltage observed at the driving point of an antenna to the strength of its received electric field.

**Electromagnetic compatibility (EMC)**: The capability of two or more electric devices to operate simultaneously without mutual interference.

**Electromagnetic interference (EMI)**: Any undesired effect of one electric device upon another due to radiated electromagnetic fields or due to voltages imposed on a shared power source.

**Elliptical polarization**: Polarization of an electromagnetic wave consisting of two perpendicular electric fields of differing phase.

**Emissions**: Fields or conducted voltages generated by an electric device.

**Far-field region**: Any location that is much farther than $\lambda/2\pi$ from an electric or magnetic field source, where $\lambda$ is the wavelength at the frequency of concern.

**Intersystem EMI**: EMI between two or more systems.

**Intrasystem EMI**: EMI between two or more parts of the same system.

**Near-field region**: Any location that is much nearer than $\lambda/2\pi$ to an electric or magnetic field source, where $\lambda$ is the wavelength at the frequency of concern.

**Open-field site**: A test location free of any conductors that would affect electromagnetic fields and taint the results.

**Polarization**: The direction of the electric field, $E$, of an electromagnetic wave.

**Power density**: Radiated power per unit of cross-sectional area.

**Radiated coupling**: Coupling due to radiated electric, magnetic, or electromagnetic fields.

**Site attenuation**: A measure of the degree to which electromagnetic fields at a test site are disturbed by environmental irregularities, obtained by comparing calculations with measured experimental results.

**Susceptibility**: The degree to which an electric device is affected by externally generated fields or conducted voltages.

**Transverse electromagnetic (TEM) cell**: A relatively small test chamber in which fields can be accurately controlled by its geometric properties.

References


Further Readings


